GENOMES to LIFE
BIOLOGICAL SOLUTIONS FOR ENERGY CHALLENGES
U.S. DEPARTMENT OF ENERGY
INNOVATIVE APPROACHES ALONG UNCONVENTIONAL PATHS

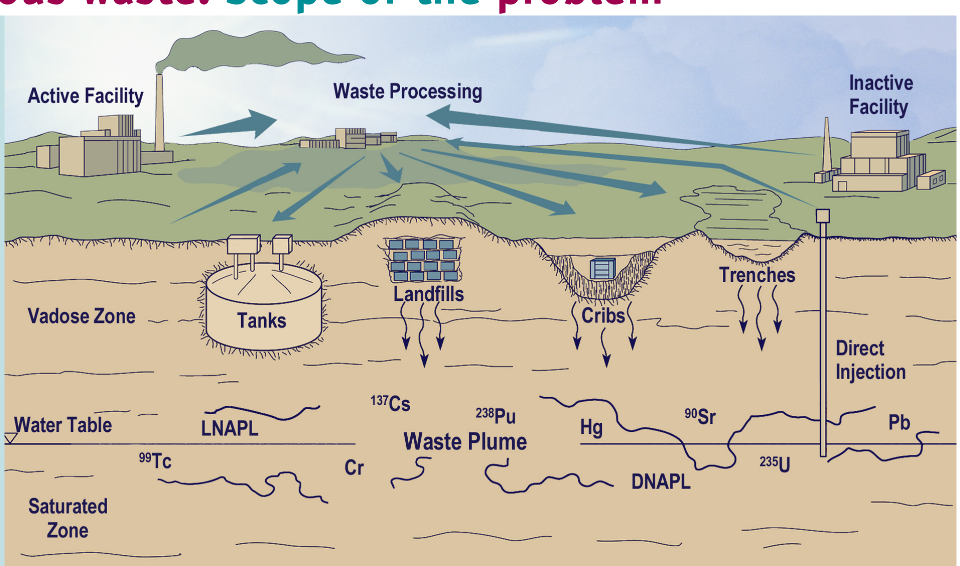
Innovative Approaches for Cleaning Up and Treating Hazardous Wastes at DOE Sites

Environmental contamination and buildup of hazardous wastes are the unfortunate legacies of half a century of nuclear weapons manufacture and storage during the Cold War (see figure below). Fundamental knowledge emerging from basic research programs in DOE's Office of Biological and Environmental Research promises to revolutionize future approaches to these challenges. New environmental-restoration and waste-treatment solutions based on biotechnology will minimize threats to human health and offer opportunities for long-term stewardship of DOE lands.

Today, scientists have in hand the complete DNA sequences of genomes for many organisms—from microbes to mice to humans. For the first time, they can explore and put to use the "operating systems" of life written into the genetic codes. With its overarching goal of using these resources to meet the challenges of critical DOE missions, the Genomes to Life program is at the leading edge of this great frontier.

Genomes to Life seeks to reveal how genomes work so researchers can predict the responses of microorganisms in different environments. Microbes, which have evolved for some 3.8 billion

A legacy of hazardous waste: Scope of the problem



For more than 50 years, the United States created a vast network of facilities for research and development, manufacture, and testing of nuclear weapons and materials. The result is that more than 7000 sites at over 100 facilities across the nation have subsurface contamination, more than half of which contains metals or radionuclides and most including chlorinated hydrocarbons. DOE is responsible for remediating 2 trillion gallons of contaminated groundwater and 75 million cubic meters of soil and subsurface sediment. The groundwater volume is equal to about 4 times the U.S. daily water consumption, and the sediment volume would fill 17 professional sports stadiums. DOE estimates that, using current technology, cleanup will take 70 years at a cost of $300 billion.

years to establish niches in virtually every environment, long ago found ways to adapt to specific environmental challenges. These adaptations may be applicable to problems for which scientists and engineers still are seeking solutions. Understanding them will allow the biological capabilities of various microbes—nature's simplest and most abundant organisms—to be exploited in meeting environmental challenges related to DOE missions.

Environmental Restoration

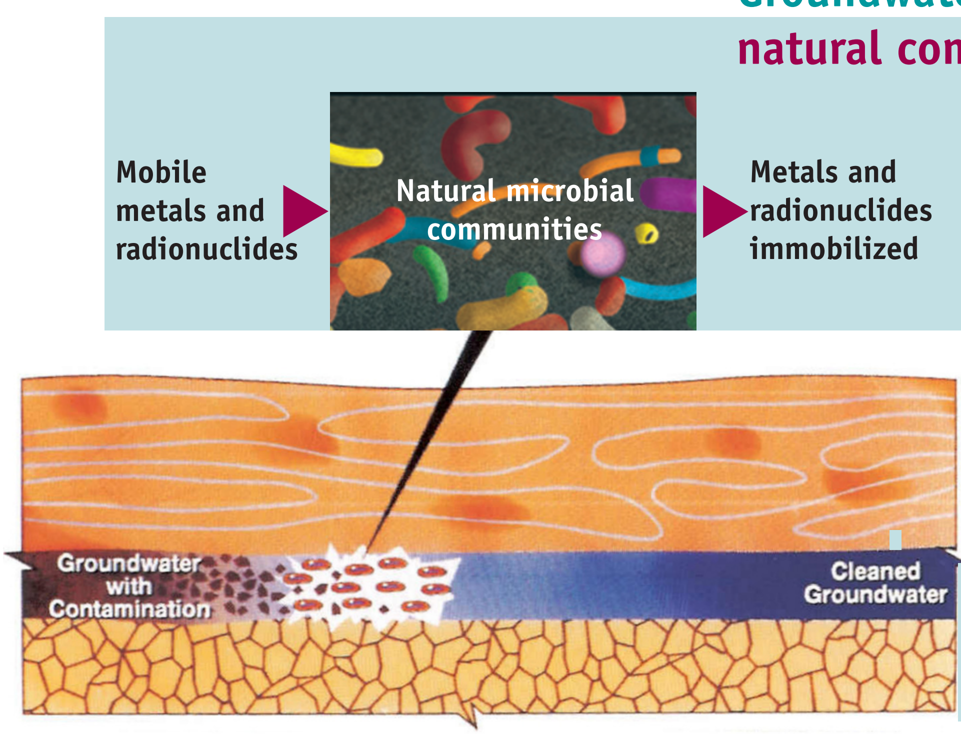
Sometimes contaminants are dispersed and often deep in the ground. In these situations, traditional excavation or pump-and-treat cleanup methods either are prohibitively expensive or technically impossible to implement. Biotechnology offers one of the most promising approaches by immobilizing contaminants in place without having to collect and transport them to an industrial facility for treatment.

Bioremediation is the use of microbes to contain, eliminate, or decrease hazardous and radioactive wastes to environmentally safe levels. For organic contaminants, bioremediation involves transforming them to benign products like carbon dioxide. Metals and radionuclides must be immobilized to prevent subsurface travel to rivers or underground sources of water. Such a barrier can be created by the in-place stimulation of natural bacterial communities that live in subsurface environments (see figure below).

Taking full advantage of these biological capabilities requires a much more complete understanding of fundamental microbial processes from the simplest to the most complex. Genomes to Life, a basic science program, is poised to develop this vital understanding in the following ways:

- Identify and characterize the multiprotein complexes ("protein machines") that perform most cell functions in microbes,
- Determine how the operations of these machines are orchestrated to allow organisms to thrive in a wide range of environments,
- Recognize the metabolic capabilities of complex microbial communities in their natural environments, and
- Develop new computational methods and tools to advance understanding of complex biological systems and predict their behavior.

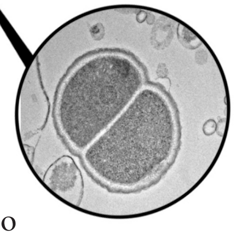
Groundwater remediation using natural communities of bacteria



Biostimulation of metal-reducing bacteria can create zones of activity within which metals and radionuclides are immobilized—in essence, a subsurface biobarrier.

Soil bioremediation using natural processes of microbial communities

A new species of radiation-resistant *Deinococcus* has been isolated from radioactive sediment beneath a leaking Hanford waste tank.



Knowledge gained in Genomes to Life can be applied to (1) predict cell behavior in a dynamic subsurface setting by integrating protein research with new computational models and (2) develop novel ways to enhance bacterial metabolism for treatment of hazardous waste.

Waste Treatment

DOE also is responsible for treating more than 70 million gallons of toxic liquid waste, over half of which is contained in 171 large underground storage tanks at a single site at Hanford in southeastern Washington State. Much of the waste is highly radioactive, and some leaky tanks continue to pose a threat to groundwater. Vitrification into glass logs is the current treatment of choice for the most highly radioactive of these tank wastes, but scientists also are looking toward developing biological treatment methods that take advantage of the ability of many microbes to tolerate and even thrive in extremes of ionizing radiation, temperature, acidity, or alkalinity (see figures, this page).

Regardless of final disposition, the processing and treatment of all materials must separate out select radionuclides. Microorganisms or their cell-free enzyme systems can remove metals and radionuclides selectively from dilute waste streams. One possibility might be to engineer microbial enzymes in a cell-free system to selectively filter out uranium, plutonium, and other metals under the very hot and alkaline conditions in the waste tanks (see figure, p. 4).

Potential Cost Savings

Over the past decade, estimates of cleanup costs across the DOE complex have tripled from $100 billion to $300 billion. Any attempt to quantify potential cost savings from biotechnology can be no more than a rough calculation, but the potential clearly is for many tens of billions of dollars.

Off-site effluent waste-treatment technologies

There are some real-world examples and comparative studies of the cost of biotechnology compared to alternate methods. At DOE's Savannah River site in Aiken, South Carolina, bioremediation of subsurface solvent contamination was two-thirds the cost of pump-and-treat and 40% more efficient. An Environmental Protection Agency study of 150 sites that use bioventing (a form of in situ bioremediation) showed cost savings of 50% to 90%. There are no direct comparisons for metals and radionuclides, but calculations project that bioimmobilization of these contaminants would be significantly less costly than in situ vitrification.

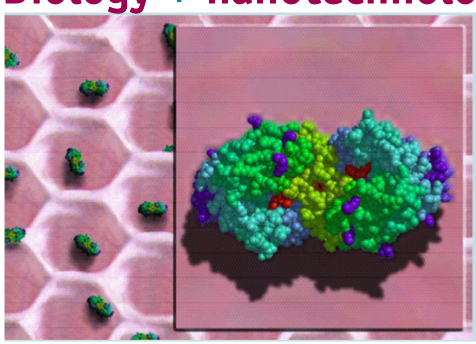
Biotechnology for Cleanup and Stewardship

Genomes to Life research will explore the capabilities of microbial communities and learn how to use them in both cleanup and long-term environmental stewardship. Naturally occurring microbial communities may be induced to express genes that control the precipitation of metals and radionuclides, and novel biosensors (e.g., microbes that fluoresce when they come in contact with radiation or other toxic substances) will allow scientists to monitor and control bioremediation strategies carried out in place. Other methods based on engineered protein machines combine miniaturization technologies and biological components to create systems that do not require living microbes (see figure below). These are just a few of the many possible solutions that Genomes to Life will help provide to the most difficult environmental problems in years to come.

Potential Impact of Bioremediation

- **About half the 7000 DOE waste sites are contaminated with radionuclides and metals, and half of them (1500 sites) are amenable to biotreatment.**
- **These sites represent 25% of $300 billion ($75 billion) estimated for cleanup using currently available technology.**
- **Range of savings with biotechnology is 30% to 50%.**

Biology + nanotechnology for waste treatment



Cell-free protein machines embedded in self-assembled mesoporous membrane systems (called SAMMS) offer an innovative way to use biotechnology for waste treatment. Early experiments show enhanced biocatalytic lifetimes.

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